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Research article

Technologies and countermeasures for gas recovery enhancement

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Abstract

Since 2000, China has been ranked as one of the top countries in gas production. Nevertheless, the domestic gas production can hardly satisfy the need of national economic development. Besides, an increasing number of gas fields have come to the middle or late development stages, and most gas reservoirs have low recovery efficiency due to the low permeability and water drive nature. Therefore, gas recovery enhancement has become an urgent issue. At present, the oil recovery enhancement is well defined, and there are methods describing the remaining oil and a complete set of mature EOR (enhanced oil recovery) technologies. However, the definition and description of EGR (enhanced gas recovery) are still undermined, and the description method for the distribution of residual gas and EGR technologies are almost unavailable. In view of this, by reviewing a wealth of related literatures, we defined EGR and also described the remaining gas distribution based on the remaining gas abundance. In addition, collecting three typical types (low-permeability, condensate and edge/bottom water) of major gas reservoirs developed both at home and abroad, we summarized the geological and development characteristics, and found out the obstructions in the development. In response, we concluded and analyzed the relevant technologies and methods for enhancing the gas recovery of such reservoirs, and proposed the suggestions about EGR technology development, which provides a significant reference and popularization basis for EGR measures in fields.

Keywords: Natural gas; Reservoir; EGR (enhanced gas recovery); Low-permeability gas reservoir; Condensate reservoir; Edge/bottom water drive gas reservoir; Technology; Countermeasure

1. Introduction of EGR (enhanced gas recovery)

As a kind of cleaner, higher-quality, more economic energy and industrial chemical, natural gas plays a more and more important role in the national economy, and 21st century will be the one of natural gas [1,2]. A majority of gas reservoirs are featured by low-permeability, water-flooding and low gas recovery factor. In addition, natural gas consumption in China rapidly rises year by year. Therefore, EGR plays a vital role in national economy and society. EGR, i.e., enhanced gas recovery, refers to the technologies, approaches or processes applied to enhance gas recovery factor on the basis of current economic and technological conditions as well as gas recovery factors obtained from natural depletion like water drive and gas drive. In terms of an oil reservoir, primary oil recovery refers to natural depletion, secondary oil recovery refers to water injection for supplementing reservoir energy, and tertiary oil recovery or EOR refers to gas injection or chemical flooding. While as for gas reservoir development, primary gas recovery refers to natural depletion development and EGR refers to other technologies and approaches capable of enhancing recovery factor of remaining gas or reservoir producing level like putting back on the production of watered-out well, water-injection, gas-injection, chemical-injection and water-plugging oil reservoir recovery factor is the product of oil displacement efficiency and sweep efficiency. EOR is focusing on improving oil displacement efficiency (such as chemical flooding) and sweep efficiency (such as gas-drive). As for middle and high-permeability gas reservoirs, there will have pressure drop so long as any well is producing and the corresponding sweep efficiency can be regarded as 100%. Well in-filling for such kind of gas reservoir can only increase

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the gas recovery rate, rather than the gas recovery factor. As for low-permeability tight gas reservoirs, gas reservoir recovery factor can be enhanced through well in-filling or horizontal well drilling due to its small pressure sweep area. As for dry gas reservoirs, relatively higher gas reservoir recovery factor can be achieved and the gas displacement efficiency is uninvolved in case of no waterflooding or other injection treatments. The residual gas distribution correlates positively with reservoir pressure, which can be applied to describe residual gas distribution. As for water-flooding or gas injection reservoir, the residual gas abundance rather than pressure distribution is preferred to describe the residual gas distribution of it due to the existence of gas displacement efficiency. The gas recovery factor of such kind of gas reservoir is relatively low due to the low gas displacement efficiency of waterflooding and corresponding water-block effect.

In this paper, we systematically investigated the mainstream EGR technologies used in low-permeability gas reservoirs, condensate gas reservoirs and edge/bottom-water gas reservoirs that have been developed up to now. Based on case studies, the applicable EGR technologies of different kinds of gas reservoirs are summarized and the EGR development suggestions are proposed.

2. EGR technologies for low-permeability gas reservoirs

The gas production contribution of low-permeability gas reservoirs is rising year by year in China. Industry experts state that stable production and production increase of natural gas in China will depend more on the production of low-permeability gas reservoirs. Therefore, more and more attentions will be drawn to the exploration and development of low-permeability gas reservoirs in China. From a geologic perspective, low-permeability gas reservoirs are featured by strong heterogeneity, high shale content, low porosity and low permeability, high capillary pressure, high water saturation, complex gas-water distribution, etc. Gas reservoir development performances include low natural productivity, rapid pressure decrease, rapid production decline, and serious well-bore liquid loading in the middle/late development period. Unreasonable development modes will result in early large-scale water breakthrough, abnormally high reservoir abandonment pressure and low gas recovery factor. Commercial gas output can only be obtained by implementing some stimulations, and the common methods include drilling horizontal wells and fracturing vertical wells.

Stimulation in low-permeability gas reservoirs runs throughout the entire process from geology, well drilling, well completion, gas reservoir engineering to reservoir decommission. The primary goal of reservoir stimulation is to increase well productivity, ultimate recovery factor, and ultimately improve economic profits by increasing reservoir permeability. The EGR technologies for low-permeability gas reservoirs are summarized as in Table 1.

In view of the geology and development characteristics of low-permeability sandstone gas reservoirs in China and considering current tight gas reservoir development experiences, the following suggestions are proposed:

1) A breakthrough need to be made in the technologies in the enriched area optimization and reservoir prediction due to the low-abundance and strong-heterogeneity of low-permeability tight gas reservoirs, and the favorable area that are applicable to economic development should be developed preferentially.
2) Tight gas reservoirs are featured by high flow resistance, starting pressure, strong stress sensitivity etc., and the traditional continuum flow theory is no longer applicable. Therefore, it is necessary to develop flow theory in non-continuous porous media.
3) Domestic and overseas practices show that horizontal wells are an effective means of the development of low-permeability tight gas reservoirs. The multi-stage fracturing technology for horizontal wells and multi-layer fracturing technology for vertical wells should be developed with independent intellectual property.
4) Low-permeability tight gas reservoirs are developed by a large number of wells and the corresponding controlled areas are small. Well-infilling is an effective means to enhance gas recovery factor and it is of great necessity to identify the economic limit of well-infilling.
5) Down-hole throttling technology has been widely and successfully applied in Sulige gas field. This technology can save investment and simplify process and is worthy of further promotion.
6) Low-permeability gas reservoirs are usually featured by low productivity and poor profit, and many gas reservoirs have reached the margin of economic development. Therefore, cost-reduction development technologies must be promoted in the whole development process.
7) Shortage of water resources in China limits the application of large-scale hydraulic fracturing technology and exploding stimulation technology in reservoir should be promoted.

3. EGR technologies for condensate gas reservoirs

Condensate gas reservoirs are a kind of special and complex gas reservoir with very high economic benefit. Currently, most of the condensate gas resources that have been discovered in China are distributed in Xinjiang province and offshores. High-content and large reserves of condensate oil in the Tarim Basin are unparalleled in China. Most condensate gas reservoirs in China are middle-low condensate oil content saturated gas reservoirs. Natural depletion is mostly adopted, resulting in low recovery factor, and some reservoirs have entered middle/late development periods. Therefore, the key issue is how to improve the recovery factors of condensate gas and condensate oil in these condensate gas reservoirs [16,17].

There are complex physical and chemical phase transitions in the development of condensate gas reservoirs, which results in complex development mechanisms and great development difficulties. As a result, there will be a lot of inevitable issues influencing productivity and condensate oil recovery factor, such as liquid damage, hydrate blockage, wellbore liquid loading and gas breakthrough. For effectively developing condensate gas

Table 1
EGR technologies for low-permeability gas reservoirs.

Technology	Advantage	Case analysis
Further understanding of reservoir geology	Improve the reliability of a geological model; reduce development cost; achieve economic and effective development.	The development mode shifts from "high production allocation" to "low production allocation" in Sulige gas field [3].
Horizontal well	Long well section crossing gas reservoirs, large controlled reserves. Greatly increase gas flow area, significantly decrease gas flow resistance.	Cleveland tight sandstone gas field [4] in Texas; Moxi low-permeability gas field in central Sichuan Basin, Daniudi low-permeability gas field, etc [5].
Gas reservoir fracturing	In favour of achieving reasonable match between well patterns and artificial fractures. Improve gas flow conditions and remove reservoir damage near wellbores.	Large-scale fracturing treatment and CO_2 foam fracturing treatment in Daniudi gas field [6].Hydraulic fracturing treatment of tight gas reservoir [7] in the south of North Sea (SNS). Delayed cross-linking fracturing fluid in the tight gas reservoir of the Xinchang, Shaximiao Fm [8].Fracturing with low-concentration thickener and low sand ratio fracturing fluid in Suining Fm gas reservoir of Luodai gas field [9].
Gas well production with water withdrawal	Reduce bottom-hole backpressure, maintain regular production of low-pressure and low-production gas wells. Extend gas well production life.	Foam withdraw gas recovery treatment in Xinchang gas field [10].Production string optimization, high-pressure gas lift, water withdraw gas recovery with pluger gas lift in Hubuzhai gas field [11]. Water withdraw gas recovery treatment with ESP in the water-out region at the edge of Xu-2 Fm gas reservoir, Zhongba gas field [12].
Separate transportation according to Pressure	Remove the interference of high-pressure gas wells on the regular production of low-pressure gas wells.	Penglaizhen Fm gas reservoir of Xinchang gas field in the Sichuan Basin [13].
Supercharging production	Reduce the input pressure of production well row, accordingly reduce gas reservoir depletion pressure. Maintain stable production of a gas reservoir.	Penglaizhen Fm gas reservoir of Xinchang gas field in Sichuan Basin [14].
Gas reservoir protection	It is important to the discovery, economic and effective development of low-permeability gas reservoirs.	Under-balanced drilling technology in Qiongxi gas field of western Sichuan Basin [15]. Acid soluble and temporary plugging well completion fluid system (ASS-1) in Sulige gas field
Well in-filling	Increase sweep volume	Sulige gas field, Daniudi gas field

reservoirs, the geology, gas reservoir type, condensate oil content and economic indicators should be considered comprehensively to design more reasonable development program.

Condensate gas reservoirs produce both natural gas and condensate oil and are usually high profit. However, there exist phase transitions and retrograde condensation in the development of condensate gas reservoirs, which results in complex development mechanism. As for the condensate gas reservoirs with high condensate oil content, the formation pressure must be controlled to be higher than dew point pressure as far as possible to prevent massive loss of condensate oil in formations. Meanwhile, as for the condensate gas reservoirs with edge/bottom water, water should be prevented from invading. The EGR technologies for condensate gas reservoirs are summarized in Table 2.

The following section is some suggestions on the EGR enhancement of condensate gas reservoirs:

1) Pressure-maintaining development is an effective means to enhance the recovery factors of condensate oils. However, the laboratory experiment results and theories of reverse-evaporation in dry gas injection are not completely consistent with practice. For example, the condensate oil recovery factor of dry gas injection treatment in Yaha gas field is higher than prediction. Therefore, directional testing technologies for real-time evaporation of gas injection need to be further researched.
2) Gravity overlap effect is also a new discovery in recent years, which cannot be described by a theoretical model in the process of gas injection. Description of this effect involves in gravity differentiation theories, non-equilibrium phase state and non-equilibrium diffusion theories, but these theories still need further study.
3) Some fracture-cavern, fractured and low-permeability condensate gas reservoirs have been discovered in recent years, and the corresponding development mechanisms are more complex than that of sandstone condensate gas reservoirs. Therefore, EGR technologies for this kind of reservoirs need to be further researched, and sing-well soaking technology is ineffective to enhance condensate oil recovery.
4) The phase state is less affected by waterflooding in condensate gas reservoirs and the gas-oil ratio does not rise. However, the sweep efficiency decreases due to waterflooding in a majority of condensate gas reservoirs. Waterflooding can be carefully applied under the conditions of high permeability and gravity drive.
5) Enhancing condensate oil recovery and enhancing gas recovery should be equally treated in the new technology development of removing condensate gas well damage. The traditional understanding only focusing on enhancing condensate oil recovery should also be changed in the development of condensate gas reservoirs.

Table 2
EGR technologies for condensate gas reservoirs.

Technology	Classification	Advantage	Case analysis
Gas injection	Dry gas injection	It is widely believed that dry gas injection treatment is more effective than any other non-hydrocarbon gas injection in the reverse-evaporation of condensate oil near wellbores, furthermore, it is free from separation and corrosion	Sleipnerφst Ty strong waterflooding gas reservoir [18]; Margham condensate gas field in Dubai [19]
	CO_2 injection	CO_2 injection is more efficient than dry gas injection in the reverse imbibition of water. CO_2 injection is more efficient than N_2 injection and CH_4 injection in removing condensate oil damage near wellbores.	Fractured condensate gas fields in Iran [20]
	N_2 injection	N_2 can sweep the oil in low-permeability zones that can not be swept by water. N_2 plays a favourable role in plug-removal, cleanup, gas displacement and gas lift through energy release due to its better compressibility and expansibility	Xinchang gasfiled [21]; Hughes Ranch East Field condensate gas field with high-content condensate oil [22]
	Air injection	High-temperature oxidation and low-temperature oxidation have been successfully implemented in oil reservoirs.	Shengli oilfield [23]
	C_3H_8 injection	Effectively reduce retrograde-condensation liquid saturation	Overseas experiments [24]
	Gas dump injection	Develop two gas reservoirs in a unique system	Jilake condensate gas field [25]
	Rich gas injection	Greatly reduce gas−liquid interfacial tension, increase the mobility of condensate oil	Vuk Till condensate gas field in Russia [26]
	$C_4H_{10} + C_5H_{12}$ injection	Miscible with condensate liquid, reduce flow resistance	Numerical simulation [27]
Liquid injection	Water injection	Low-cost, appropriate waterflooding mobility ratio, improve three-phase displacement, maintain gas reservoir pressure, does not change gas composition and dew point pressure	KazakhstanrⅢ condensate oil & gas reservoirs [28], Banqiao abandoned condensate gas reservoir [29]
	CH_3OH injection	The volatility of CH_3OH is in favour of displacing the reverse-imbibition of water near wellbores and removing water block. Reduce gas−liquid interfacial tension	Hatter's Pond oilfield [30], well Pu 8-12 in P67 condensate gas reservoir [31]
	Diesel oil injection + surfactant	Effectively remove condensate oil block and improve gas production	Hatter's Pond oilfield [32]
Co-injection of liquid and gas	Water-alternating gas injection	Effectively improve the sweep volume of injected gas, prevent gas breaking-through. Substantially increase the condensate oil recovery factor of layered condensate gas reservoirs	Experiments and numerical simulations of Hughes Ranch East Field condensate gas field in USA [33]
	CH_3OH slug injection + dry gas injection	CH_3OH pre-slug removes retrograde-gas-condensate damage and reverse-imbibition water block. Dry gas recedes the effect of retrograde condensation again	Deep condensate gas reservoir of Zhongyuan oilfield in southern Yellow River region [34]
	(C_2H_6, C_3H_8, C_4H_{10} or Liquid Gas) Slug Injection + Single-Well Soaking by Dry Gas Displacement	The effect of condensate oil re-accumulation is lesser and the overall treatment effect is better than that of dry gas injection	Vuk Till condensate gas field [35]
Wettability alteration	Surfactant and polymer	Improve liquid-phase mobility through wettability alteration, increase the productivity of condensate gas well	Azerbaijan offshore gas field [36], Dongpu gas field [37]
Horizontal well	Development by horizontal wells	Large drainage area, lower drawdown than vertical wells, higher productivity	Yaha condensate gas field [38], Sulige gas field [39]

(*continued on next page*)

Table 2 (*continued*)

Technology	Classification	Advantage	Case analysis
Key Technologies of Stable Production	Reservoir protection technologies	Reservoir protection is essential to gas wells, reduce differential pressure, prevent oil from condensing, maintain gas reservoir productivity	All can be taken into consideration
	Gas reservoir fracturing technologies	Improve bottom-hole flowing conditions, reduce differential pressure, enhance recovery factor and production	Condensate gas reservoir in Wennan oilfield [40]
	Gas recovery by liquid withdraw	Remove bottom-hole liquid loading, maintain gas well regular production	Baimiao condensate gas reservoir [41]

6) Although the published EGR technologies have been listed in Table 2, some of them are still in evaluation stage and have not been put into field application, and specific reservoir properties, current technologies and economic conditions must be considered in the application of these technologies.

4. EGR technologies for edge/bottom-water gas reservoirs

A majority of gas reservoirs in China are categorized as waterflooding gas reservoirs with different waterflooding levels, and the gas reservoirs with active edge/bottom water account for 40%−50%. From a geologic perspective, most edge/bottom-water gas reservoirs are anticlinal traps and faults are often well-developed. Most gas reservoirs are classified as active water-invasion gas reservoirs and featured by low porosity, low permeability and strong heterogeneity. Gas reservoirs are usually invaded by formation water along fractures, which greatly reduces gas recovery factor. Compared with gas-drive gas reservoirs, the development of edge/bottom-water gas reservoirs is featured by low gas recovery rate, rapid production decline, low recovery factor, significant rise of water-gas ratio, large investment, high cost, etc. Therefore, the water production performances of wells and reservoirs must be monitored carefully in the development and relevant water-control technologies should be further researched.

Table 3
EGR technologies for edge/bottom-water gas reservoirs.

Technology	Advantage	Case analysis
Water withdraw gas recovery by production string optimization	Rational utilization of producing energy	Daniudi gas field [42]
Water withdraw gas recovery by foam	Easy implementation, short term, low cost and does not influence regular production	Sebei gas field [43], Huabei oilfield [44]
Water withdraw gas recovery by gas lift	Easy to design, install and mange, lower investment, more output	Jingbian gas field [45], Wenan gas field [46]
Water withdraw gas recovery by pumping	Applicable to water-out gas wells which are featured by a certain productivity, high water production, relatively high producing liquid level and no adjacent high-pressure gas source or water-out gas wells for which gas lift treatment can not be economically implemented	Songjiachang gas field, Longtou-Diaozhongba gas reservoir [47]
Water withdraw gas recovery by ESP	Easy to adjust parameters, design, install and maintain; suitable for putting back on the production of water-out gas wells and gas reservoirs with high water production	Xu2 gas reservoir in Zhongba gas field [48], Well Tai 7 in Guizhou gas field [49]
Water withdraw gas recovery by jet pump	Applicable to withdraw corrosive fluid and sand-laden fluid, deviated wells and horizontal wells, high-temperature deep wells. Easy to install, low maintenance cost. Wide production interval, easy to control	Naxi gas field [50], Songjiachang gasfield [51], Xushen gas field [52]
Water withdraw gas recovery by ESP + capillary effect	Better foaming effect through directly injecting foaming agent to the designed position	Shunan Gas Production Plant, PetroChina Southwest Oil & Gasfield Company [53]
Water withdraw gas recovery by turbine-pump	High reliability, easy to adjust, low weight, compact dimensions, high temperature resistance and corrosion resistance	Turtle-Bayou gas field [54]
Concentric capillary technology	Effectively and economically solve practical problems such as liquid loading in low-pressure gas wells, corrosion protection of oil & gas wells, salt scaling removal and wax removal.	Cotton Valley gas field in East Texas, USA [55]
Gas recovery by continuous gas cycling	Compensate the disadvantages of Plunger lift and velocity string	Qzona gas field [56]
Strategic water control	Forced water withdraw in water regions or water-flowing channels, prevent gas reservoirs from being invaded by water	Xu2 gas reservoir in Zhongba gas field [57]

A majority of edge/bottom-water gas reservoirs with high water-invasion level have entered middle-late development periods in China. In order to obtain an optimum water withdraw effect, technical features and applicability of various water withdraw treatments must be carefully considered in the application of artificial gas recovery by water withdraw. Through years of research and development, respective technologies in enhancing the recovery of edge/bottom-water gas reservoirs have been developed both at home and abroad. The EGR technologies for edge/bottom-water gas reservoirs are summarized in Table 3.

The following section is the EGR suggestions for edge/bottom-water gas reservoirs:

1) Reservoir pressure should be reduced to be free of acquifer influence through normalizing the re-production technology of water-out gas reservoirs and accelerating gas recovery by water withdraw. When the reservoir pressure is further reduced, the entrapped gas swells and flows into gas wells. This technology has been applied in many gas fields in the USA and the Former Soviet Union.
2) Based on the gas-water two-phase flow resistance, non-hydrocarbon gases are injected to displace natural gas and prevent water invasion. In view of the density difference between N_2 and CH_4, N_2 is injected into the region between gas the reservoir and water. N_2 plug can both prevent water invasion and displace natural gas. This technology has been applied in Medvezhye gas field in Russia.
3) Edge/bottom-water gas reservoir numerical simulations and physical simulations should be performed to establish numerical cores and new methods to combine simulation properties of physical and numerical simulations with water invasion mechanisms of gas recovery by water withdraw and gas detection by water withdraw.
4) Water withdraw gas recovery technologies should be further researched, including combined gas recovery by water withdraw, water withdraw gas recovery by coiled tubing in deep gas wells, ultrasonic water withdraw gas recovery, water withdraw gas recovery by pig lift and gas lift valve technology.
5) Pilot test of well dual-completion treatment need to be performed. A new method of enhancing gas recovery factor was proposed by Armenta et al., which installs both a withdraw system and an injection system at the bottom hole.
6) Reservoir rock wettability near a well-bore is changed by injecting the chemical agent. Gas phase becomes wetting phase, which will maintain the mobility of gas phase after water breakthrough.

5. Conclusions

1) EOR technologies cannot be directly applied to EGR due to the difference between them in definition and residual oil/gas description methods.
2) EGR technologies for low-permeability gas reservoirs focus on reducing abandonment pressure and increasing sweep volume.
3) The primary goal of EGR in condensate gas reservoirs is to not only enhance condensate oil recovery but also enhance natural gas recovery.
4) EGR technologies for edge/bottom water gas reservoirs tend to concentrate on water control, water utilization and water-block removal, and the water invasion mechanism in complex gas reservoirs needs to be further researched.
5) Currently, many complex gas reservoirs (example, low-permeability condensate edge/bottom-water gas reservoir) have been discovered in China, and reasonable EGR programs have to be designed according to the major contradictions of them.

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